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Design of Switched Filter Bank using Chebyshev Low pass Filter Response for Harmonic Rejection Filter Design

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Abstract - *Harmonic is a serious problem faced by the power amplifier in its working. These are introduced into the power amplifier due to the nonlinearities of the active element such as the transistor in the power amplifier. As a result, the power quality and safe operation become inferior. Therefore the mitigation of harmonics and improvement in the power quality are essential under these circumstances. This paper presents the design of a switched filter bank for using Chebyshev low pass filter response for the design of Harmonic Rejection Filter. Advanced Design System is used for simulation purpose. The obtained results show that each filter bank rejects its harmonic frequencies successfully with a return loss >16 dB.*

Key Words: **Harmonics, Switched Filter Bank, Chebyshev Low pass Filter, Harmonic Rejection Filter, Advanced Design System, Return Loss.**

1. INTRODUCTION

During 20th century, evolutions in radios, communications and radars increased the demand for electromagnetic spectrum. Since the demand for Radio Frequency Spectrum has increased and become commercialized for different applications like mobile communications, television and radio communications, a clean radiation spectrum is a must for each radio transmissions. This has to be ensured by the RF front end of each radio transmitters. The RF front end section includes power amplifiers and they introduce harmonics to the signal and these harmonics are a multiple of operating frequencies and causes serious impurities in the spectrum. A demand for higher data rate implies a demand for higher bandwidth for the radio spectrum. This makes the elimination of the harmonics tougher for the RF front-end modules.

This motivates the need for an in-house Harmonic Rejection Filter technology in India. The Harmonic Rejection Filter is basically a low pass filter which passes the fundamental frequency and attenuates the higher harmonic frequencies. Passive filters have low cost, simple design and high reliability than active filters. Chebyshev filters have better rate of attenuation beyond passband than Butterworth filters. This paper presents the design of a switched filter bank using Chebyshev low pass filter for the design of Harmonic Rejection Filter.

2. METHODOLOGY

Chebyshev filters or equiripple filters have a steeper roll-off and more passband ripple than Butterworth filters. The analytic form of the squared magnitude function is defined by

$$|H(j\omega)|^2 = \frac{1}{1+\varepsilon^2 T_n^{\,2}\left(\frac{\omega}{\omega_p}\right)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where ε is the ripple factor, $T_n(x)$ is the Chebyshev polynomial of degree n and ωp is the passband edge frequency. Closed form expressions for the Chebyshev polynomial are given by

$$T_n(x) = \begin{cases} \cos(n\cos^{-1}x), & |x| < 1\ (Stopband) \\ \cosh(n\cosh^{-1}x), & |x| > 1\ (Passband) \end{cases} \dots\dots (2)$$

be defined by a recursion formula:

$$T_n(x) = 2xT_{n-1}(x) - T_{n-2}(x), n > 1 \dots\dots\dots\dots\dots\dots (3)$$

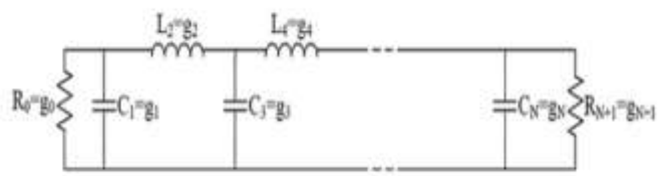
where $T_0(x)=1$ and $T_1(x)=x$. The order of the Chebyshev

filter is given by the equation:

$$n \geq \frac{\cosh^{-1}\left(\sqrt{\frac{10^{0.1A_s}-1}{10^{0.1A_p}-1}}\right)}{\cosh^{-1}\left(\frac{\omega_s}{\omega_p}\right)} \; or \; \geq \frac{\cosh^{-1}\left(\frac{\sqrt{(A^2-1)}}{\varepsilon}\right)}{\cosh^{-1}\left(\frac{\omega_s}{\omega_p}\right)} \dots\dots (4)$$

where A_s is the minimum stopband attenuation in dB, A_p in the maximum passband ripple in dB, $\varepsilon = (10^{0.1Ap}-1)^{1/2}$ is the ripple factor, $A = (10^{0.05As})^{1/2}$ is the user-defined stopband attenuation parameter, ω_s is the stopband edge frequency in rad/sec and ω_p is the passband edge frequency in rad/sec.

There are two types of LC Ladder networks for Low pass filters as Pi and Tee Section. Pi section prototype starts with a shunt element, whereas Tee section starts with a series element. At the beginning of the circuit $g_0 = 1$ is defined as generator resistance or capacitance. The last element at the end is defined as g_{N+1} which is the load resistance if g_N is a shunt capacitor and load conductance if g_N is a series inductor. The type of the prototype used in the design of the filter is Pi section as in Figure 2.1



The Chebyshev low pass filter prototype element values are given by the following equations:

$$g_1 = \frac{2a_1}{\gamma} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$g_k = \frac{4a_{k-1}a_k}{b_{k-1}g_{k-1}}, k = 2,3, \ldots\ldots, n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

g_1 and g_k are the capacitor or inductor element values. The coefficients β, γ, a_k and b_k can be calculated from the following equations:

$$\beta = ln\left[\coth\left(\frac{\alpha_{dB}}{17.372}\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\gamma = \sinh\left(\frac{\beta}{2n}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

$$a_k = \sin\left(\frac{(2k-1)\pi}{2n}\right), k = 1, 2, \ldots\ldots\ldots, n \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

$$b_k = \gamma^2 + sin^2\left(\frac{k\pi}{n}\right), k = 1, 2, \ldots\ldots\ldots, n \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where α_{dB} is the passband ripple in dB. The number 17.372 is rounded from the exact value 40/ln (10). The low pass filter element values are given by

$$L_k = \frac{Z_o g_k}{\omega_c}\ nH\ and\ C_k = \frac{g_k}{Z_o \omega_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where Z_o is the characteristic impedance in ohm and $\omega_c=2\pi f_c$ is the angular frequency in rad/sec, f_c is the cut-off frequency of the filter in Hz.

3. RESULT AND DISCUSSIONS

In this paper, 30-512 MHz frequency range is assumed to be divided into six filter banks and each filter bank has been simulated separately in the Advanced Design System (ADS) environment.

3.1 Filter Bank 1: 30-50 MHz

Here, 30-50 MHz filter bank operates on 30-50 MHz band which passes up to 50 MHz with a passband ripple of -0.1 dB and start offering rejection from 50 MHz (cut-off frequency) with a stopband frequency of 60 MHz which offers a rejection around -24 dB. Table-1 shows the circuit parameters used in this simulation.

Pass band Frequency, ω_p	30-50 MHz
Stopband Frequency, ω_s	60 MHz
Pass band Ripple	-0.1 dB
Stopband Rejection	-24 dB
Filter Order, n	9

Table-1: Circuit Parameters

Table-2 shows the inductor and capacitor values used in this schematic design.

Inductor	$L_1 = L_4$	$L_2 = L_3$	L_5
Values	229.60 nH	257.31 nH	-
Capacitor	$C_1 = C_5$	$C_2 = C_4$	C_3
Values	76.119 pF	135.89 pF	140.40 pF

Table-2: Inductor and capacitor values

Fig-1 shows the schematic design for ADS simulation.

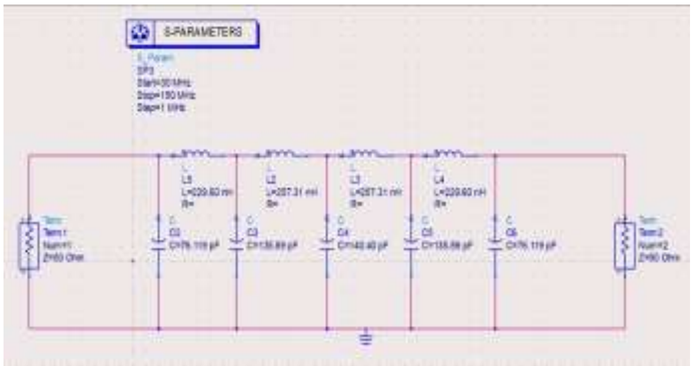


Fig-1: Schematic Design

Fig-2 shows the ADS simulation results and observations.

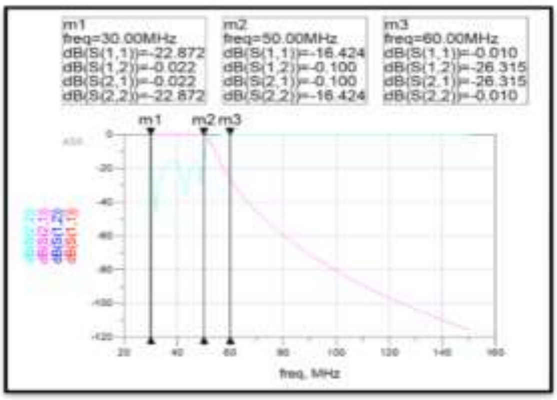


Fig-2: Simulation result

Here the color cyan represents the Chebyshev filter response and the color magenta represents the Low pass filter response. From the plot, it is clear that the signal is passed up to the cut-off frequency, 50 MHz and beyond the cut-off frequency, known as harmonic frequency, 60 MHz, the signal is rejected with a stopband rejection of -24 dB. From the plots, it is clear that for a filter bank 1 with passband ripple (-0.1 dB) and stopband rejection (-24 dB) will have a return loss, R_L= -16.424 dB.

3.2 Filter Bank 2: 50-85 MHz

Here, 50-85 MHz filter bank operates on 50-85 MHz band which passes up to 85 MHz with a passband ripple of -0.1 dB and start offering rejection from 85 MHz (cut-off frequency) with a stopband frequency of 100 MHz which offers a rejection around -24 dB. Table-3 shows the circuit parameters used in this simulation.

Pass band Frequency, ω_p	50-85 MHz
Stopband Frequency, ω_s	100 MHz
Pass band Ripple	-0.1 dB
Stopband Rejection	-24 dB
Filter Order, n	9

Table-3: Circuit Parameters

Table-4 shows the inductor and capacitor values used in this schematic design.

Inductor	$L_1 = L_4$	$L_2 = L_3$	L_5
Values	135.06 nH	151.36 nH	-
Capacitor	$C_1 = C_5$	$C_2 = C_4$	C_3
Values	44.776 pF	79.935 pF	82.587 pF

Table-4: Inductor and capacitor values

Fig-3 shows the schematic design for ADS simulation.

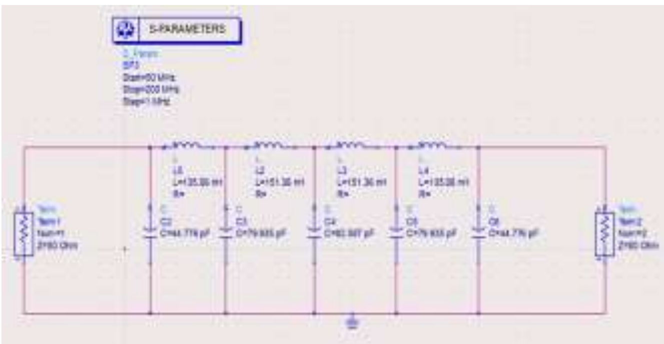


Fig-3: Schematic Design

Fig-4 shows the ADS simulation results and observations.

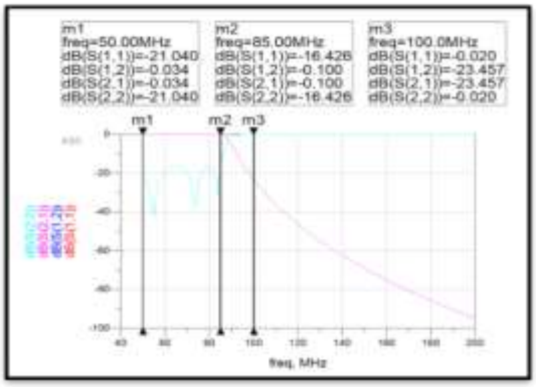


Fig-4: Simulation result

Here the color cyan represents the Chebyshev filter response and the color magenta represents the Low pass filter response. From the plot, it is clear that the signal is passed up to the cut-off frequency, 85 MHz and beyond the cut-off frequency, known as harmonic frequency, 100 MHz, the signal is rejected with a stopband rejection of -24 dB. From the plots, it is clear that for a filter bank 2 with passband ripple (-0.1 dB) and stopband rejection (-24 dB) will have a return loss, R_L= -16.426 dB.

3.3 Filter Bank 3: 85-142 MHz

Here, 85-142 MHz filter bank operates on 85-142 MHz band which passes up to 142 MHz with a passband ripple of -0.1 dB and start offering rejection from 142 MHz (cut-off frequency) with a stopband frequency of 170 MHz which offers a rejection around -24 dB. Table-5 shows the circuit parameters used in this simulation

Pass band Frequency, ω_p	85-142 MHz
Stopband Frequency, ω_s	170 MHz
Pass band Ripple	-0.1 dB
Stopband Rejection	-24 dB
Filter Order, n	9

Table-5: Circuit Parameters

Table-6 shows the inductor and capacitor values used in this schematic design.

Inductor	$L_1 = L_4$	$L_2 = L_3$	L_5
Values	80.844 nH	90.602 nH	-
Capacitor	$C_1 = C_5$	$C_2 = C_4$	C_3
Values	26.802 pF	47.848 pF	49.436 pF

Table-6: Inductor and capacitor values

Fig-5 shows the schematic design for ADS simulation.

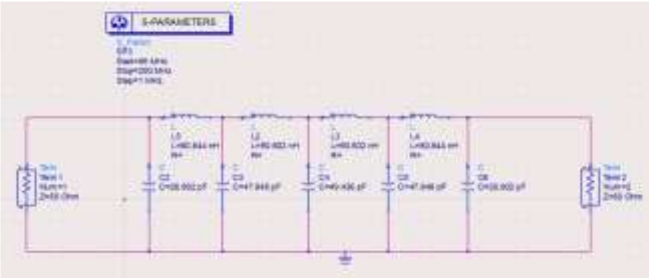


Fig-5: Schematic Design

Fig-6 shows the ADS simulation results and observations.

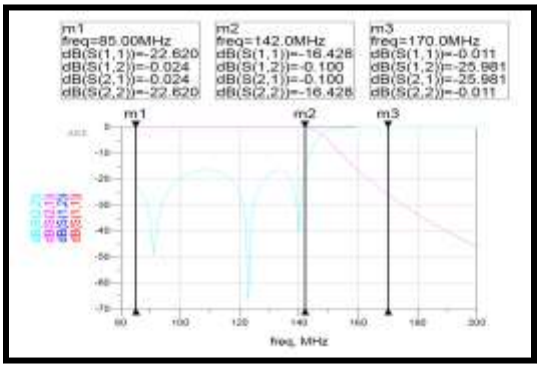


Fig-6: Simulation result

Here the color cyan represents the Chebyshev filter response and the color magenta represents the Low pass filter response. From the plot, it is clear that the signal is passed up to the cut-off frequency, 142 MHz and beyond the cut-off frequency, known as harmonic frequency, 170 MHz, the signal is rejected with a stopband rejection of -24 dB. From the plots, it is clear that for a filter bank 2 with passband ripple (-0.1 dB) and stopband rejection (-24 dB) will have a return loss, R_L= -16.428 dB.

3.4 Filter Bank 4: 142-236 MHz

Here, 142-236 MHz filter bank operates on 142-236 MHz band which passes up to 236 MHz with a passband ripple of -0.1 dB and start offering rejection from 236 MHz (cut-off frequency) with a stopband frequency of 284 MHz which offers a rejection around -24 dB. Table-7 shows the circuit parameters used in this simulation.

Pass band Frequency, ω_p	142-236 MHz
Stopband Frequency, ω_s	284 MHz
Pass band Ripple	-0.1 dB
Stopband Rejection	-24 dB
Filter Order, n	9

Table-7: Circuit Parameters

Table-8 shows the inductor and capacitor values used in this schematic design.

Inductor	$L_1 = L_4$	$L_2 = L_3$	L_5
Values	48.644 nH	54.515 nH	-
Capacitor	$C_1 = C_5$	$C_2 = C_4$	C_3
Values	16.127 pF	28.790 pF	29.745 pF

Table-8: Inductor and capacitor values

Fig-7 shows the schematic design for ADS simulation.

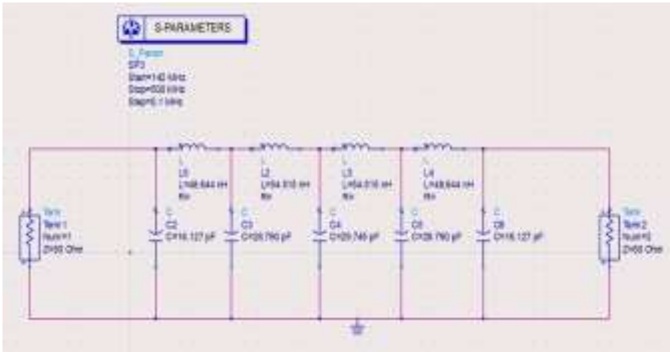


Fig-7: Schematic Design

Fig-8 shows the ADS simulation results and observations.

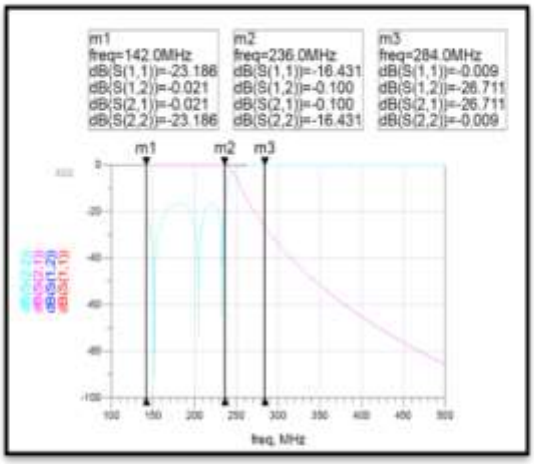


Fig-8: Simulation result

Here the color cyan represents the Chebyshev filter response and the color magenta represents the Low pass filter response. From the plot, it is clear that the signal is passed up to the cut-off frequency, 236 MHz and beyond the cut-off frequency, known as harmonic frequency, 284 MHz, the signal is rejected with a stopband rejection of -24 dB. From the plots, it is clear that for a filter bank 2 with passband ripple (-0.1 dB) and stopband rejection (-24 dB) will have a return loss, R_L= -16.431 dB.

3.5 Filter Bank 5: 236-394 MHz

Here, 236-394 MHz filter bank operates on 236-394 MHz band which passes up to 394 MHz with a passband ripple of -0.1 dB and start offering rejection from 394 MHz (cut-off frequency) with a stopband frequency of 472 MHz which offers a rejection around -24 dB. Table-9 shows the circuit parameters used in this simulation.

Pass band Frequency, ω_p	236-394 MHz
Stopband Frequency, ω_s	472 MHz
Pass band Ripple	-0.1 dB
Stopband Rejection	-24 dB
Filter Order, n	9

Table-9: Circuit Parameters

Table-10 shows the inductor and capacitor values used in this schematic design.

Inductor	$L_1 = L_4$	$L_2 = L_3$	L_5
Values	29.137 nH	32.654 nH	-
Capacitor	$C_1 = C_5$	$C_2 = C_4$	C_3
Values	9.6597 pF	17.245 pF	17.817 pF

Table-10: Inductor and capacitor values

Fig-9 shows the schematic design for ADS simulation.

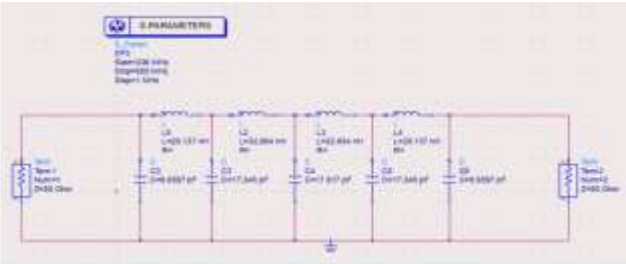


Fig-9: Schematic Design

Fig-10 shows the ADS simulation results and observations.

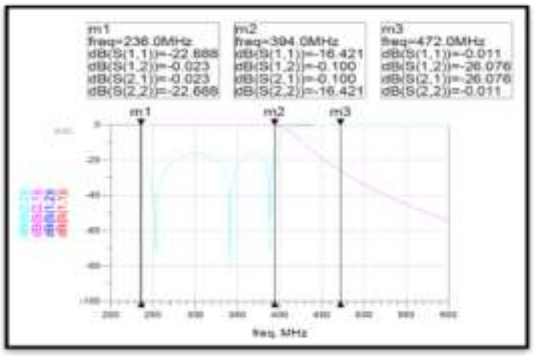


Fig-10: Simulation result

Here the color cyan represents the Chebyshev filter response and the color magenta represents the Low pass filter response. From the plot, it is clear that the signal is passed up to the cut-off frequency, 394 MHz and beyond the cut-off frequency, known as harmonic frequency, 472 MHz, the signal is rejected with a stopband rejection of -24 dB. From the plots, it is clear that for a filter bank 2 with passband ripple (-0.1 dB) and stopband rejection (-24 dB) will have a return loss, R_L= -16.421 dB.

3.6 Filter Bank 6: 394-512 MHz

Here, 394-512 MHz filter bank operates on 394-512 MHz band which passes up to 512 MHz with a passband ripple of -0.1 dB and start offering rejection from 512 MHz (cut-off frequency) with a stopband frequency of 788 MHz which offers a rejection around -24 dB. Table-11 shows the circuit parameters used in this simulation.

Pass band Frequency, ω_p	394-512 MHz
Stopband Frequency, ω_s	788 MHz
Pass band Ripple	-0.1 dB
Stopband Rejection	-24 dB
Filter Order, n	5

Table-11: Circuit Parameters

Table-12 shows the inductor and capacitor values used in this schematic design.

Inductor	$L_1 = L_2$	L_3
Values	21.312 nH	21.312 nH
Capacitor	$C_1 = C_2$	C_3
Values	7.1297 pF	12.279 pF

Table-12: Inductor and capacitor values

Fig-11 shows the schematic design for ADS simulation.

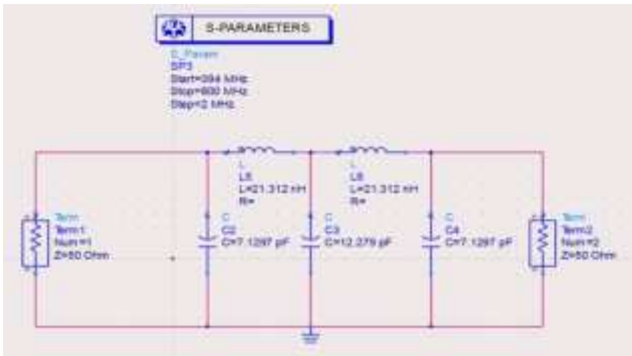


Fig-10: Schematic Design

Fig-12 shows the ADS simulation results and observations.

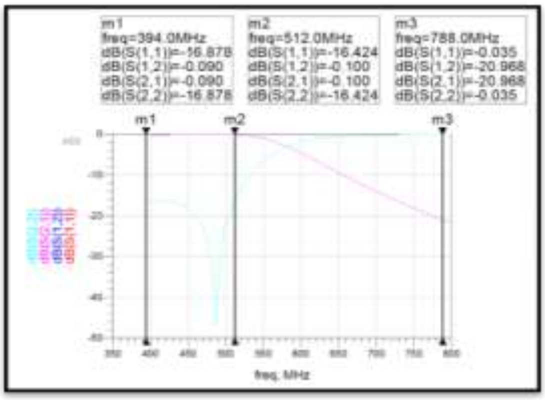


Fig-12: Simulation result

Here the color cyan represents the Chebyshev filter response and the color magenta represents the Low pass filter response. From the plot, it is clear that the signal is passed up to the cut-off frequency, 512 MHz and beyond the cut-off frequency, known as harmonic frequency, 788 MHz, the signal is rejected with a stopband rejection of -24 dB. From the plots, it is clear that for a filter bank 2 with passband ripple (-0.1 dB) and stopband rejection (-24 dB) will have a return loss, R_L= -16.424 dB.

4. CONCLUSION

In this paper, the design of a 6 channel switched filter bank for 30-512 MHz frequency range using Chebyshev low pass filter response for the design of Harmonic Rejection Filter was presented. The proposed filter bank improves the power quality by rejecting the harmonic frequencies with a return loss >16 dB. The obtained results meet the IEEE 519 recommended harmonic standards.

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